Using Satellite Ocean Colour to Explore Phytoplankton Dynamics and Size in East Australian Waters

Student: Leonardo Laiolo

B.Sc. (Biological Sciences)
M.Sc. (Marine Biology)

Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Science.

August 2018

Supervisors:

Prof. Martina Doblin

Dr. Richard Matear

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Leonardo Laiolo declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Science at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

Production Note:
Signature: Signature removed prior to publication.

Date: 23rd August 2018

ACKNOWLEDGEMENTS

I would like to thank all the people who made this PhD possible. Thank you Martina, for giving me the opportunity to do the PhD, for always encouraging me and for your logistical support. Thanks Richard, for everything you taught me, for always challenging me and for showing me the creative side of science, this has become part of me. Thanks to Monika and Allison, for your help and your patience, I learnt so much from you both and not just about science. I'm really glad for the friendship that arose from our collaborations. Mark thanks for the insightful and understanding discussions during my PhD. I would like to thank the Marine National Facility staff, the amazing crew and scientists I met aboard the *RV Investigator*. The four voyagers that I have been involved in during my PhD would have to be amongst the toughest, yet rewarding days of the past three years.

Thanks to my partner and best friend Emily, for showing me the bright side of everything even on the stressful days. Ana and Giulia, I wish to thank you for making me feel at home, and always being there to listen. Daniel, thanks for the chilled evenings at home after the hard days at work, it was a pleasure sharing that quirky house with you. Thanks to the Tasmanian waves, that always brought me peace and mindfulness even on the toughest days. And thanks to the boys of Taroona Football Club, for being welcoming since the first day and making me feel part of a soccer team, a joy that reminds me of home.

Thanks to my family for being understanding, supportive and so enthusiastic to maintain constant contact, despite the distance with me living across the world. Last but not least, thanks to myself for never giving up, maintaining high spirits following my passions.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

come from the CSIRO Atlas of Regional Seas (CARS) available at http://www.marine.csiro.au/~dunn/cars2009/. Data for B comes from seasonal climatology of the downward short wave radiation at the surface of the ocean (Large and Yeager 2008).

Figure 2.4: Seasonal climatology of cold core CE (solid blue lines) and warm core ACE (solid red lines) eddies for: A) mixed layer depth (MLD) (GODAE); B) surface chlorophyll-a concentration (GlobColour). The light blue and light red areas represent standard deviation for CE and ACE, respectively.

Figure 2.5: WOMBAT's acceptable solutions obtained from data assimilation. Left column shows ACE seasonality and right column CE seasonality. The red solid lines in plots A and B show the Chl-a observed seasonal climatology with the red shading denoting the standard deviation variability. In all remaining plots, the blue areas represent WOMBAT acceptable solutions. Plots C (ACE) and D (CE) represent primary production (g C m^{-2}) while plots E and F represent the zooplankton dynamics for the ACE and CE systems, respectively.

Figure 2.6: EMS acceptable solutions from the data assimilation. Left column shows ACE seasonality and right column CE seasonality. The red solid lines in plots A and B show the Chl-a observed seasonal climatology with the red shading denoting the standard deviation variability. Patterns of the two EMS phytoplankton classes (Chl-a) are represented in plot C (ACE) and D (CE), where red areas represent the large phytoplankton class (40 µm diameter) and blue areas represent the small phytoplankton class (2 µm diameter). Plots E (ACE) and F (CE) represent the total primary production (g C m^{-2}) in black and the primary production for small (blue) and large phytoplankton (red). The total zooplankton biomass (g C m^{-2}) is represented in black on plots G (ACE) and H (CE), while the small and large zooplankton biomass is represented in blue and red, respectively.

Figure 2.7: Pigment analysis of phytoplankton in different treatments (shipboard incubation experiment): A) size distribution at the initial and

final time of the experiment; B) ratio between characteristic phytoplankton classes pigment and total Chl-*a* (Diatoms: Fucoxanthin, Haptophytes: 19-Hex-fucoxanthin, Synechococcus: Zeaxanthin, *Prochlorococcus*: DV Chlorophyll *a*, Barlow et al. (2004)). In all panels it is represented the "T0 (110m)" showing the initial condition and the "T final" showing the last day of the experiment (6th day). The treatments are labelled as: LL (20% surface irradiance), HL (40% surface irradiance), N (daily nutrients addition). The control (CON, ~1% incident light, no nutrient amendment). The CON is not represented at the end of the experiment (T final) because the pigment concentrations were below detection (>0.004 μg/L).

the dashed line (150° E – 160° E; 30° S – 40° S). **(b)** Location of the match-up points # (Table 4.1) are represented by #, while non match-up points are represented by CTD # (Table 4.2) inside circles. The background is a Globcolour Chl-*a* (mg m^{-3}) satellite field averaged from the 31^{st} August to 16^{th} September 2016. White areas indicate land or no data.

Figure 4.3: Comparison between *in situ* and satellite Chl-*a* match-up points. (a) Comparison between the size fractionated Chl-*a* and the satellite Chl-*a* through bar charts. While grey bars represent the satellite Chl-*a*, the narrow blue, green and red bars show the *in situ* Chl-*a* for the small (< 2 μm), medium (between 2 to 10 μm) and large (> 10 μm) phytoplankton class respectively. Errors bars represent the standard deviation in the 3x3 pixel box that has been used for the matchup with the *in situ* Chl-*a*. (b) Relationship between total *in situ* Chl-*a* and satellite Chl-*a*. The green solid line indicates a 1:1 relationship and dashed green lines show the ± 35% uncertainty interval.

Figure 4.4: Relationship between *in situ* Chl-*a* and satellite Chl-*a.* Red dots and corresponding red linear regression lines represent the direct comparison between *in situ* Chl-*a* vs satellites Chl-*a*. The green dots and lines show the linear fit to the remotely sensed Chl-*a* where a different weighting is given for the *in situ* Chl-*a* associated with small, medium and large phytoplankton. Panel (a) shows regression model A in red font and regression model C in green font. The regression model B (in red) and regression model D (in green) are represented in panel (b). (c) The bar chart shows the size distribution (%) of the phytoplankton community for every match-up point. Match-up point's numbers correspond to numbers in Table 4.1 and Fig. 4.2.

Figure 4.5: Bio-optical properties in different simulated scenarios obtained through the optical model (Bair et al., 2016). The three columns represent three different Chl-*a* concentration, 0.2, 1.0 and 3.0 mg m^{-3} respectively. The first three rows show the corresponding absorption, backscattering and R_{rs} for the wavelength 443 nm in function of increasing phytoplankton

LIST OF TABLES

Table 4.2: Details about the stations sampled that have no corresponding satellite match-up measurements. The table shows CTD number (CTD #), *in situ* sampling time, location, site and total Chl-*a* (TChl-*a in situ*). The contribution to the TChl-*a in situ* from the three different phytoplankton size classes (i.e., Small <2, Medium between 2 μm and 10 μm and Large >10 μm) is represented in percentages in the last columns. The “Site” column indicates stations near the continental shelf (c.s.) and off-shore stations (o.s.).

Table 4.3: Weighting applied to the *in situ* size-fractionated Chl-*a* to produce the least squares best fit to the satellite Chl-*a* values. A measure of the fit is given by R^2 values. While x corresponds to the in situ observations and y to the corresponding satellite Chl-*a*. P represents *p*-values obtained testing the data against a slope of 1, Eq. (5).

LIST OF ABBREVIATIONS

a	Absorption coefficient
ACE	Anticyclonic eddy
AOPs	Apparent optical properties
b_b	Backscattering coefficient
C	Carbon
CARS	CSIRO Atlas of Regional Seas
CDOM	Coloured dissolved organic matter
CE	Cyclonic eddy
Chl-*a*	Chlorophyll-*a* concentration
Chl-a_{lrg}	Percentage of Chl-*a* concentration in the large (> 10 µm) phytoplankton class
Chl-a_{med}	Percentage of Chl-*a* concentration in the medium between 2 and 10 µm) phytoplankton class
Chl-a_{sml}	Percentage of Chl-*a* concentration in the small (< 2 µm) phytoplankton class
CO_2	Carbon dioxide
c.s.	Continental shelf station
CV	Coefficient of variation
DA	Data assimilation
EAC	East Australian Current
EMS	Environmental Modelling Suite
IOPs	Inherent optical properties
MODIS-Aqua	Moderate Resolution Imaging Spectroradiometer
NAP	Non-algal particulates
NPZD	Nutrient, Phytoplankton,

	Zooplankton and Detritus
O_2	Oxigen
OC3M	Band ratio algorithm of Chl-*a* concentration for data from MODIS radiometer
OLCI	Ocean and Land Colour Instrument
o.s.	Off-shore station
R_{rs}	Remote sensing reflectance
RS	Regression slope
SD	Standard deviation
SE	Standard error
SeaWIFS	Sea-Viewing Wide Field-of-View Sensor
simulated OC3M Chl-*a*	Satellite-like Chl-*a* product obtained from EMS output
simulated surface Chl-*a*	*In situ*-like Chl-*a* measurements
TChl*a*	Total chlorophyll-*a*
TSS	Total suspended particles
VIIRS	Visible Infrared Imaging Radiometer Suite
WOMBAT	Whole Ocean Model of Biogeochemistry And Trophic-dynamics

ABSTRACT

The eastern Australian ocean region is strongly influenced by the East Australian Current (EAC). Waters in this region are generally oligotrophic; despite this, nutrient enrichment and phytoplankton blooms occur as a response to physical events such as the seasonal deepening of the mixed layer or the formation of cyclonic eddies. In this PhD project, biogeochemical and optical modelling, ocean color data assimilation, *in situ* measurements and ship-board experiments were used to investigate phytoplankton dynamics and size structure in offshore eastern Australian waters, information that is necessary to improve estimates of future ocean primary productivity.

First, the seasonal phytoplankton dynamics in averaged cyclonic and anticyclonic eddies (CE and ACE, respectively) off eastern Australia were explored through a single and a multi-phytoplankton class biogeochemical model. Seasonal climatologies of surface chlorophyll-*a* concentration (Chl-*a*) and mixed layer depth for both CE and ACE were obtained by combining remotely sensed sea surface height, remotely sensed ocean color and *in situ* profiles from Argo floats. Simulated phytoplankton responses to changes in nutrients and light were compared with a ship-based experiment. The experimental results were consistent with the model result, where the seasonal deepening of the mixed layer during winter produced a rapid increase in large phytoplankton. Although the Chl-*a* concentration in CE was larger than ACE, the primary production estimates obtained through the assimilation of the ocean colour product within different types of eddies were similar, showing an inconsistency with previously published studies that suggest CE are significantly more productive.

To explore the properties and relationship of the satellite ocean colour product and *in situ* observations, theoretical experiments were performed through a coupled biogeochemical-optical model. Specifically, an optical model was used to calculate the inherent optical properties (IOPs) of seawater from size dependent multi-phytoplankton

biogeochemical model simulations and convert them into remote-sensing reflectance (R_{rs}). Then, R_{rs} was used to produce a satellite-like estimate of the simulated surface Chl-*a* concentration through the OC3M algorithm. The information content of simulated *in situ* and simulated remotely-sensed data sources was investigated through theoretical experiments that suggested the OC3M algorithm underestimates the simulated Chl-*a* concentration because of the weak relationship between large-sized phytoplankton and R_{rs}.

Finally, this concept was tested with real data collected on a voyage in 2016, to investigate the relationship between the *in situ* sampled phytoplankton size structure and the corresponding satellite Chl-*a* product. Ocean colour match-up points confirmed the underestimation of *in situ* Chl-*a* concentrations when phytoplankton larger than 10 μm dominated the photosynthetic community. Furthermore, optical model simulations suggested that large phytoplankton cells cause a decrease in both the absorption and backscattering signals, which in turn affect the R_{rs} and cause the underestimation of Chl-*a* by the satellite Chl-*a* product.

To understand impacts of contemporary ocean change on regional primary productivity, we rely on biogeochemical models to scale up sparse *in situ* observations. Although ocean colour provides information at high spatial and temporal resolution, this information has limited accuracy. Results presented in this thesis show that a simultaneous assimilation of *in situ* and satellite remote sensing can provide additional information about the phytoplankton size structure, crucial data to progress our understanding of processes influencing regional primary productivity and elemental cycling. Therefore, parameter optimization through a combination of the information provided by two distinct observation platforms (*in situ* and satellite remote sensing) will lead to the development of next-generation biogeochemical models.